# Acoustic Wave Dispersion and Scattering in Complex Marine Sediment Structures

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## LONG TERM GOALS

The long term science goal is to advance understanding of the physical mechanisms that control propagation and scattering in the seabed.

## OBJECTIVES

The objectives are to draw upon those advances to a) to infer roughness and/or volume heterogeneity parameters from reflection and scattering data and b) measure dispersion in *in-situ* sediments in the frequency range of interest, 0.1-10 kHz. This work builds on prior research in disentangling dispersion from the effects of sedimentary layering and sound speed/density gradients.

## APPROACH

The approach includes both theoretical as well as measurement components. Theory is needed to better understand the relationship between sediment volume scattering from a continuum (e.g., slumps and slides) versus scattering from discrete particles (e.g., rocks, shells, or bubbles). Measurements are needed to 1) exploit the volume scattering theory for identification of the dominant mechanisms and seabed features that give rise to volume scattering, 2) quantify the effects of various mechanisms, including volume scattering and shear waves on dispersion in marine sediments and 3) provide broadband measurements (especially in muddy sediments) from which dispersion can be estimated.

## RESULTS

A brief summary of the research is provided below, which is described in detail in the referenced publications. A number of the research elements were motivated by preparation for the ONR Seabed Characterization Experiment (SCE'17).

1. *Developed theory and methodology to distinguish between the two major classes of volume heterogeneities, discrete particles or a fluctuation continuum, using spectral characteristics of scattering, see Ref [1]*. In at-sea experiments, heterogeneity characteristics generally are not known *a priori*. Thus, an uninformed model selection is generally made, i.e., the researcher must arbitrarily select either a discrete or continuum model. It was shown that it is possible to (acoustically)

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**14. ABSTRACT**
Major challenges in testing dispersion theories against measured data include separating the competing effects of structures that occur in virtually all natural marine sediments including discrete layering, gradients (sound speed, attenuation and density), shear waves, interface roughness, sediment volume heterogeneities (sub-wavelength scale), lateral variability (many wavelength scale) and anisotropy. All of these effects exhibit their own frequency dependence and if ignored, can badly bias dispersion estimates.  One of the competing effects, sediment volume scattering, is important not only for establishing the correct frequency dependence of the attenuation, but also crucial for understanding long-range reverberation prediction. Recent evidence has suggested that sediment volume scattering is a dominant mechanism for controlling the frequency dependence of reverberation. The long-term goal of the research is to substantively improve understanding of the physical mechanisms that control propagation and scattering in the seabed.

**15. SUBJECT TERMS**
sediment geoacoustic properties, heterogeneities, propagation

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discriminate between continuum and discrete heterogeneities in some instances. The ability to so discriminate is important, because there are few tools for measuring small scale, O($10^{-2}$ to $10^{1}$) m, sediment heterogeneities over large areas. Therefore, discriminating discrete vs continuum heterogeneities via acoustic remote sensing may lead to improved observations and concomitant increased understanding of the marine benthic environment. The research results are described in detail in Ref [1].

2. *With collaborators developed an improved method for estimating near surface sediment sund speed and density profiles from seabed reflection data, see Ref [2]*. The acoustics of muddy sediments has become of intense interest in the ONR community and very large and non-linear gradients have been observed in such sediments. In the past, the form of the sediment sound speed or density depth dependence was prescribed, e.g., linear or linear $n^2$ are very common. This research exploits the parsimony and stability of Bernstein polynomials to infer a completely arbitrary depth dependence. The Bernstein polynomial method was applied to measured reflection data in a muddy sediment area, where highly non-linear depth-dependent profiles were obtained – informed by the measured data (and not a subjective *a priori* model selection). This method will provide a new and substantively more objective method for estimating sediment density and sound speed depth-dependent profiles. It will be of particularly important for obtaining infomration about the muddy sediment depth-dependent profiles in the SCE'17 experimental area.

3. *With a collaborator applied the Image Source Method to AUV measurements of seabed reflection to obtain a quasi-three-dimensional map of sediment sound speed. The sound speed is obtained over a 2 km x 2 km area of high variability down to sub-bottom depths of up to 80m, see Ref [3]*. This was the first time this method has been applied to data with dipping (i.e., non-parallel) layers. The results show a numerous fine-scale details of the sedimentary structure that represent a significant advance in geoacoustic inversion. In addition this development was an important advance in preparation for the SCE'17 experiment in which similar seabed reflection data will be collected.

4. *With a collaborator developed a method for imaging sub-seabed scatterers, see Ref [4]*. While the sub-bottom fine-scale structure is of considerable interest, imaging results from acoustic data are often swamped by specular returns from sediment interfaces. This research demonstrated a method by which the specular return amplitudes are greatly reduced so that it is possible to image isolated scatterers. The method was applied to a data set collected by an AUV towing a source and receiver, where the imaging provides new evidence for the role of fault zones as a preferential path for gas/fluid migration [5]. The data show, in particular, that gas bubble slugs, i.e. discontinuous gas columns, rise through sediments along a complex system of conduits terminating at the surface into quiescent mud volcanoes. This method will also be applied to the SCE'17 data to determine the presence of gas and other sediment heterogeneities.

5. Conducted extensive experiment planning in preparation for the ONR Seabed Characterization Experiment, SCE'17, where the main focus was on muddy sediment fabrics. In order to meet the science objectives, three different measurement techniques were employed.
    a) *Wide-angle seabed reflection with a fixed mooring*. This experiment measured the seabed reflection coefficient as a function of angle (about 5-80°) and frequency 100 – 5,000 Hz using a fixed receiver and a towed source. Two receiver geometries were employed: a receiver in the water column and a long horizontal array on the seabed.

b) *Towed seabed reflection and scattering*. The seabed reflection coefficient (~25-40°) and scattering strength (~8-30°) were measured from 500 – 6000 Hz using a towed source mounted on the vibration isolation module of the Five-Octave Research Array (FORA). The tow height of source and receiver was about 10-15 m above the seabed. The objective was to estimate the 2-D (depth in sediment and along transect range) and quasi-3D sediment geoacoustic properties and provide estimates of interface and volume roughness heterogeneity parameters along the tracks.

c) *Broadband seabed scattering.* We requested our collaborators to collect these data, using Sound Undersea Signal (SUS) in relatively close proximity to a moored receiving array. These data will be used to understand small-scale fluctuations in density and sound in the mud volume as well as roughness statistics of the sand and other horizon interfaces.

The measurements and analyses of these data were and are being conducted in a follow-on project.

## PUBLICATIONS

[1] Holland C.W., G. Steininger and S. Dosso, Discrimination between discrete and continuum scattering from the sub-seafloor, J. Acoust. Soc. Am., 138, 663-673, 2015.

[2] Quijano J., S. Dosso, J. Dettmer, and C.W. Holland, Geoacoustic inversion for the seabed transition layer using a Bernstein polynomial model, J. Acoust. Soc. Am., 140, 2016.

[3] Pinson S. and C.W. Holland, Seafloor sound-speed profile characterization with non-parallel layering by the image source method: Application to CLUTTER'09 campaign data, J. Acoust. Soc. Am. (EL), 154-158, 2016.

[4] Pinson S. and C.W. Holland, Layer filtering for seafloor scatterers imaging, J. Acoust. Soc. Am. (EL), 137, 355-359, 2015.

[5] Savini A., S. Pinson, A. Bistacchi, G. Etiope and C. Holland, Imaging shallow fault-controlled migration pathways in a mud-volcano province using an Autonomous Underwater Vehicle, J. Geophysical Research – Earth Surface, in review.